



# Growth morphologies and plausible stressors ruling the formation of Late Pleistocene lacustrine carbonate buildups in the Maquinchao Basin (Argentina)

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## Funding information

Schweizerischer Nationalfonds zur Förderung der Wissenschaftlichen Forschung, Grant/Award Number: 200021\_155927 and 200021\_155927/2

## Abstract

In a seminal paper regarding the mechanisms of carbonate stromatolite formation, Ginsburg (1991, *Controversies in Modern Geology*, pp. 25–36) emphasized the need to question the relative role of microbes versus environment in their formation. The Maquinchao Basin is a continental lacustrine system in southern Argentina. It provides an ideal site to study carbonate buildups, the role of microbes and environmental stressors in their development and their implications in palaeoenvironmental reconstructions. Presently, the basin encompasses two lakes (Carri Laufquen Grande and Carri Laufquen Chica) joined by the ephemeral Maquinchao River. Fossil microbialites are found south and southwest of the largest lake. Preferential areas of development for fossil microbialites have been mapped using a high-resolution differential Global Positioning System. Outcrops are located between 820 and 830 m elevation, higher than actual lake levels and the Maquinchao River where living microbialites have been observed. Field data along with microscopical observations and X-ray diffraction analyses have revealed a heterogeneity in both distribution and macro-morphotypes since carbonate buildups display different morphologies such as crust, columns, open flower-like, rounded and ellipsoids. Conversely, on the meso and micro-scale they show more homogeneous morphologies including laminations and shrubs. These microbial buildups are associated with basaltic substrates of variable size from pebbles to boulder. The homogeneity in meso and micro-structures argue in favour of stable intrinsic parameters (i.e. microbial communities) whereas the variable macro-morphotypes indicate changing extrinsic constraints such as steepness, energy and turbidity. The occurrence of distinctive morphotypes in buildups separated by outcrop and topography suggest that the Maquinchao microbialites are indicative of a former larger lake. Thus, the Maquinchao microbial buildups are a valuable proxy for water-level evolution and therefore palaeoenvironmental reconstructions. They can be further used to interpret the apparently random distribution of morphological types and extension of microbialites in the geological past.

## KEYWORDS

Carbonate, lacustrine, microbialite, palaeoshorelines, Patagonia

## 1 | INTRODUCTION

Microbial carbonates have always fascinated scientists since they represent the earliest forms of life on Earth. Early studies mostly focused on their shape and texture setting the groundwork for a descriptive definition (Semikhatov, Gebelein, Cloud, Awramik, & Benmore, 1979) with emphasis on the lamination regardless of the abiotic or biotic origin (Grotzinger & Knoll, 1999). However, according to Krumbein (1983) the term stromatolite was coined by Kalkowsky (1908) who provided a more genetic designation by relating their formation to ‘microscopic’ activity. In recent years, there has been growing interest in understanding the organomineralization processes behind their formation (Dupraz et al., 2009). The development of new techniques allowing for nano-scale investigation has been critical in attaining this goal as well as facilitating the attempt to disentangle the role of the various biotic and abiotic processes contributing to the development of these carbonate buildups. However, the discovery of their modern counterparts presenting different microfabrics supported the dichotomy between descriptive and genetic terminology and created an overall confusion in the use of the term stromatolite. Bob Ginsburg was very concerned as to how this controversy might affect research into these carbonate buildups that have played such a prominent role in Earth history (Ginsburg, 1991). He pointed out the duality of these buildups and therefore the difficulty in separating the influence of extrinsic and intrinsic parameters, essentially the respective roles of abiotic and biotic processes in their origin. The definition of stromatolites should therefore be controlled by the fundamental differences observed between fossil and modern examples.

As in the marine realm, continental carbonates occur in various types of environments from lacustrine/palustrine and fluviatile settings to karst, soils and thermal or freshwater springs (Della Porta, 2015; Ford & Pedley, 1996; Pedley, 1990). In many settings, non-marine carbonate precipitation was primarily related to abiotic processes. Following a better understanding of marine microbialites, and more precisely stromatolites, various studies have focused on the close interaction between micro and macro-organisms such as archae, bacteria, fungi, algae, plants and the chemical parameters of the precipitating waters. Their role in both macro and microstructures has been extensively discussed by Ginsburg (1991), Couradeau et al. (2013), Farías et al. (2013), Jahnert and Collins (2011, 2012), Suosaari et al. (2016) and Vasconcelos et al. (2006) among others.

Traditionally travertine and tufa have been associated with the loss of carbon dioxide gas triggering the precipitation of

carbonate from a Ca bicarbonate-rich solution in non-marine environments (Pentecost, 2005). This process has been further related to specific environmental settings such as (hot) springs or CO<sub>2</sub>-rich water bodies. Thus, ‘extrinsic’ components have been usually considered dominant. Conversely, according to Riding (2011a) stromatolite refers to ‘laminated organosedimentary deposits that have accreted as a result of a benthic microbial community trapping and binding detrital sediment and/or forming the locus of mineral precipitation’. Thus, the previous definition relies on the presence of micro-organism communities having an active role in the precipitation of minerals and in the construction of the structure. However, more recently other authors (Pentecost, 2005) consider that microbes are also a key component in travertine/tufa formation. Microbialites were first defined by Burne and Moore (1987) and used to encompass stromatolites, thrombolites and leiloite, and more recently travertine and tufa as well (Riding, 2011a). Mineral precipitation, especially in microbialites, has been described as resulting from diverse processes and separated into two categories namely biomineralization (a), a biologically controlled mineralization by the metabolism of certain microorganisms, and organomineralization (b), a biologically mediated precipitation that can be either induced or influenced (Dupraz et al., 2009). The two major elements leading to mineral precipitation in organomineralization are physicochemical—alkalinity—and microbial components. In the first case, it is an ‘extrinsic’ parameter depending on the environment and therefore to some extent could be considered as abiotic. The second case represents an ‘intrinsic’ factor highly dependent on microbial assemblages, the development of exopolymeric substances and other biological factors. In this case, it becomes very difficult to disentangle the abiotic/biotic processes particularly in non-active and fossil systems (Dupraz et al., 2009).

Carbonate precipitation is also highly dependent on water chemistry. However, the shape and extension of many carbonate constructions vary not only with microbial communities but also with the prevailing energy and other environmental stressors (Della Porta, 2015; Jahnert & Collins, 2012; Roche et al., 2018). In fact, Ginsburg (1991) expressed the potential for stromatolites to act as sedimentary structures, their morphologies being driven by environmental factors such as currents, type of substrate or physical changes in the environment. Therefore, fossil microbialites can be powerful tools, acting as proxies for both chemical and physical parameters (Andrews & Brasier, 2005; Frantz et al., 2014; Petryshyn, Corsetti, Berelson, Beaumont, & Lund, 2012; Solari, Hervé, Le Roux, Airo, & Sial, 2010). Freshwater stromatolites in

particular have been used as indicators of lake-level changes due to their distribution along lake shorelines (Casanova & Hillaire-Marcel, 1993). Analogously, laminations in both travertine and stromatolites have been related to regional climate forcings (Pentecost, 2005; Petryshyn et al., 2012).

In the Maquinchao Basin, located in northern Patagonia (Argentina) carbonate constructions have been described as tufa (Cartwright et al., 2011; Galloway, Markgraf, & Bradbury, 1988) and stromatolites (Pacton et al., 2015; Tatur et al., 2002). Previous studies in the area include the evolution of the present lakes through time using seismic profiles and sedimentary cores, ostracods auto-ecology and their stable isotope compositions (Ariztegui, Anselmetti, Gilli, & Waldmann, 2008; Ariztegui, Anselmetti, Kelts, Seltzer, & D'Agostino, 2001; Coviaga et al., 2018; Cusminsky et al., 2011; Schwalb, Burns, Cusminsky, Kelts, & Markgraf, 2002; Whatley & Cusminsky, 1999), lake-level variations (Cartwright et al., 2011; Galloway et al., 1988; Tatur et al., 2002) and the formation of modern microbialites (Pacton et al., 2015). This contribution focuses on the Pleistocene carbonate buildups and their occurrence in the Maquinchao Basin. Defining the environmental stressors controlling their distribution and describing their characteristics at different scales are critical to provide a more precise definition of these carbonate buildups while determining the external and internal factors ruling their formation. Formulating a plausible model to explain the formation of these carbonate buildups will provide a better picture of the environmental impact late Pleistocene climate variations had on the Maquinchao Basin. This contribution represents the first step towards developing such a model that might be further applied to other microbialites developed in similar environments at different geographical and temporal scales.

## 2 | STUDY SITE: PRESENT CLIMATE AND HYDROLOGY—GEOLOGICAL AND SEDIMENTOLOGY CONTEXT

The study site is a closed basin located in the northern part of Argentinian Patagonia in the Rio Negro province (41°08'S and 69°28'W). The Maquinchao Basin is about 10,690 km<sup>2</sup> and sits between the Atlantic Ocean coast and the Andean foothill city of San Carlos de Bariloche. The region is characterized by a median annual temperature of 10°C, annual mean precipitation of 200 mm/year and regular wind speeds of 100 km/hr (SMN 1981-2010; Agosta, Compagnucci, & Ariztegui, 2015).

The area is a tectonic depression with an elevation of 800 m a.s.l. surrounded by Miocene basaltic plateaus on both the west and east sides of the basin that exceed 1,000 m asl. The geographical position of the Maquinchao Basin

precluded its involvement in the last glaciation (Ariztegui et al., 2008; Rabassa & Clapperton, 1990). Currently, it contains two main lacustrine bodies, the Carri Laufquen Grande (CLG) at 781 m a.s.l. and the Carri Laufquen Chica (CLC) at 821 m a.s.l. The CLG is a 6 × 5 km body of brackish water with a mean water depth of 2 m (data from January 2011; Pacton et al., 2015). The CLC is smaller, extending 4 × 2 km with an average depth of 3 m and characterized by freshwater (data from January 2011; Pacton et al., 2015). Both lakes are joined by the ephemeral freshwater Maquinchao River. They have developed on a succession of Mesozoic volcanic deposits, clays, calcareous sandstones and conglomerates, together with Miocene volcanoclastic and volcanic deposits (Whatley & Cusminsky, 1999). Finally, the Pleistocene sequence is represented by fluvial and lacustrine deposits (Coira, 1979).

Historical satellite data show that both lakes had substantial water-level fluctuations during the last ten years (Departamento Provincial de Aguas (DPA) 2012). Clear palaeoshorelines are evident on the east side of CLG, previously dated at 19 ka (Galloway et al., 1988) and between 14 ka and 10–8 ka BP (Bradbury, Grosjean, Stine, & Sylvestre, 2001) revealing a former lake high stand. In addition, several palaeoclimate studies using different proxies indicate higher lake-level stands during the late Pleistocene (Ariztegui et al., 2008; Coviaga et al., 2018; Galloway et al., 1988; Tatur et al., 2002; Whatley & Cusminsky, 1999).

Previous studies described the occurrence of carbonate buildups related to the lacustrine deposits (Ariztegui et al., 2008; Cartwright et al., 2011; Pacton et al., 2015; Tatur et al., 2002). Most of these fossil carbonate buildups were generally described as complex structures of globular, medium size open flower-like to large open flower-like morphologies. They are located at altitudes varying between 822 and 830 m that are above the present altitude of CLC (821 m approximately), CLG (781 m approximately) and the Maquinchao River. In addition, Pacton et al. (2015) investigated the modern microbialites growing in certain sectors of the freshwater Maquinchao River presenting similar globular-like morphologies as some fossil examples.

## 3 | MATERIALS AND METHODS

Field investigations were carried out during several campaigns between December 2015 and April 2018 by a multidisciplinary research team of both Swiss and Argentinian scientists. One of the main goals was to precisely identify and accurately locate the carbonate buildups outcropping within the basin. Carbonate buildups were mapped using a geographical information system platform (ArcGIS 10.1) in combination with ALOS Global Digital Surface Model (DEM) data (spatial resolution 30 m) and a field survey using a Trimble R2 differential GPS (dGPS). The vertical precision of the dGPS (i.e.



$\pm 10$  cm) provide a clear distribution, extension, and altitude of the different carbonate buildups. The identification of one outcrop was based on a combination of different features, the prevailing one being lateral continuity. In cases where discontinuity exceeds 100 m, similarities in the mega and macro structures were used to determine outcrops. This strategy allows the identification of different buildup types that were further related at different macro and microscopical scales. Outcrops of carbonate buildups have only been mapped if they extend for more than 2 m<sup>2</sup> and contain at least 20 individual structures. Additionally, a water data survey has been established in the Maquinchao Basin by sampling water at CLG, CLC and the Maquinchao River where living microbial mats were located. Basic parameters such as pH, temperature, conductivity and major elements were determined at different seasons of the year to better characterize the hydrology of the basin. The full dataset will be published independently as a hydrological contribution presently under preparation.

Field and laboratory investigations include (a) macrostructural analyses on a metre to centimetre scale; (b) mesostructural analyses, incorporating a study of the internal structure of individual bodies visible by naked eye, and (c) microstructural investigations, encompassing petrographic microscopy and Scanning Electron Microscopy (SEM) observations as well as X-ray diffraction (XRD) determinations. Due to the friable character of some samples, petrographic analyses were carried out on impregnated thin sections. Impregnations were made with a bi-component epoxy resin (Araldit® XW396/XW 397). Mineralogical analyses were performed at the University of Geneva with XRD diffractograms obtained using a Philips X'pert, equipped with a PW3710 MPD diffractometer and a PW3020 vertical goniometer. Additionally, Energy Dispersive Spectroscopy (EDS)

analyses were carried on both bulk samples and thin-sections. Elemental spectra were acquired using the Energy dispersive X-ray analyser EDS JED2300 (SEM).

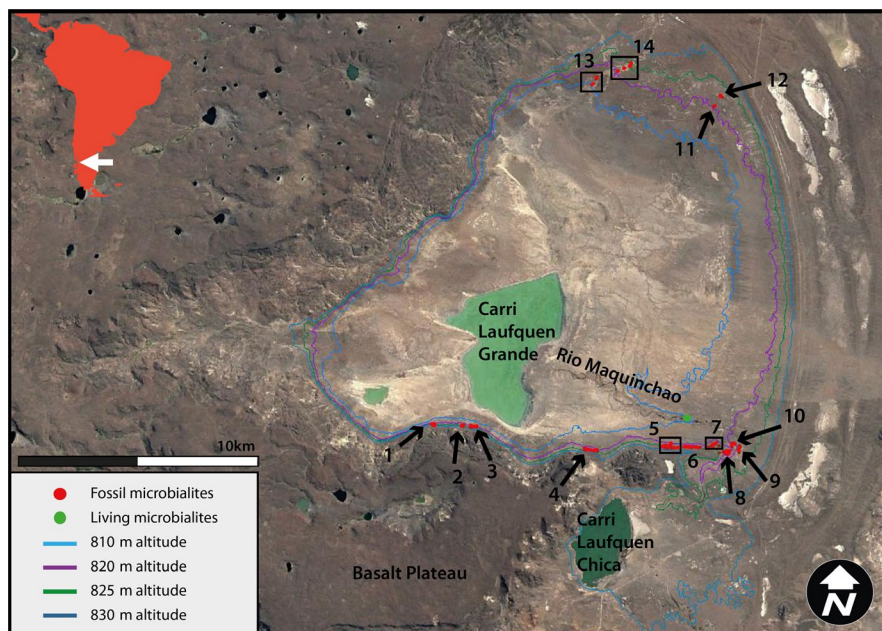
## 4 | RESULTS

### 4.1 | Types and growth morphologies of the carbonate buildups















Most of the landscape around the Carri Laufquen lake system is composed of soils and very recent fluvial and lacustrine sediments encompassing very fine silt, sand and minor gravels depending on the location. Carbonate buildups are often well preserved (full pieces) but in certain cases also display partially eroded morphologies. Additionally, broken pieces are associated with the preserved buildups at the different outcrops. Fourteen main outcrops were defined following the criteria described previously (see Section 3). Outcrops of carbonate buildups were found south of CLG and north to northeast of CLC (Figure 1; Table 1) at least 30 m above CLG present lake level. Six different morphological types of carbonate buildup were distinguished among these 14 outcrops. They are summarized in Table 2 with most of these morphological types observed in several outcrops.

The different morphological types include carbonate crusts of variable thickness, large open flower-like structures, linked columnar forms, medium open flower-like assemblies as well as ellipsoid and rounded shapes. In addition to the individual morphologies, both size and coalescence—or not—form part of the definition of these constructions. The preservation of these carbonate buildups is variable. The same morphologies within a single outcrop often have a visible nucleus whereas others do not show it. Morphologies such as

**FIGURE 1** Satellite image of the Maquinchao Basin showing the location of both modern lakes Carri Laufquen Grande (CLG) and Carri Laufquen Chica (CLC) as well as the Maquinchao River and the different outcrops discussed in the text (Google, Landsat/Copernicus)



**TABLE 1** Outcrop description and main characteristics

Outcrops	Altitudes	N-sample range	Main carbonate morphology	Substrate granulometry	Schema
01	826.8–830.7 m	80–100	Coalescent crust	Boulder–cobble	
02	825.8–827.5 m	15–20	Large open flower-like	Cobble	
03	822.3–822.7 m	50–60	Medium open flower-like	Cobble	
04	825–825.6 m	60–70	Large open flower-like	Boulder–cobble	
05	821.7–825.5 m	100–110	Small to medium size ellipsoid	Pebble–coarse to very coarse	
06	824.9–825.7 m	100–110	Small rounded; Small ellipsoid	Pebble–coarse to very coarse	
07	825.8 m	100–110	Small rounded; Small ellipsoid	Pebble–coarse to very coarse	
08	822.8–823.1 m 824.5–825.3 m	100–120	Linked columns Small to medium ellipsoid+small coalescent	Pebble–coarse	
09	823.6–824.2 m	50–60	Small rounded	Pebble–very coarse	
10	823.4–824.5 m	35–40	Linked columns	Pebble–coarse	
11	820.8–821.2 m	60–65	Small rounded	Pebble–coarse	
12	823.3 m	100–110	Small rounded	Pebble–coarse	
13	816.5 m	20	Small to very small ellipsoids	Pebble–coarse	
14	824.3–824.8 m	80–85	Small to medium ellipsoid	Pebble–coarse to very coarse	

the open flower-like or smaller rounded ones with a clearly visible nucleus in the centre characterize less well-preserved constructions. The following paragraphs contain a detailed description of the differentiated morphological types.

#### 4.1.1 | Crusts

Crusts cover large areas enveloping pebble to boulder-size basalt assemblages and/or other lithologies (Figure 2A). Crust thickness varies from 2 to 5 cm presenting a surface texture ranging from flat and smooth to globular. Crusts dominate the steep basaltic outcrops located at altitudes between ~827 m and ~831 m south of CLG (Figure 3).

#### 4.1.2 | Large open flower-Like








Flower-like structures represent the largest type of carbonate buildup (Figure 2B and C) and these typically develop around a sizeable basaltic nucleus. The carbonate construction is quite thick compared to the previously described crusts, with thicknesses of at least 15 cm. Each individual piece can have a diameter varying between 50 and 80 cm and although standing as single units they often appear at the

same altitudinal level either on an almost flat area or forming a single line along the same altitudinal level on steep outcrops. These buildups have a variable degree of preservation with the well-preserved external part showing a characteristic texture ranging from very smooth to uneven or lumpy. Large open flower-like forms are found along the south ridge of CLG between 825 m and ~826 m and ~826 to 828 m in areas with abundant basalt cobbles and boulders. These flower-like structures may be half buried, especially at outcrop 4.

#### 4.1.3 | Linked columns

Linked columnar morphologies outcrop as banks (Figure 2E) with the columns either connected or separated by a few centimetres to up to a metre. Their height ranges from 20 to 30 cm from the prevailing substrate of small basalt pebbles, visible at the base of the columns as a lumpy external texture. They can be found either fully preserved or partially eroded lacking the central part but with the outer structure preserved. Well preserved buildups present a rounded flat upper part. Columns are often buried and therefore better preserved than other buildups. These banks are found at both shores of the present Maquinchao River bed at ~823 and ~825 m altitude.

**TABLE 2** Types of morphologies and their dominant features

Type name	Crusts	Large open flower-like	Linked columns		Medium open flower like	Small to medium ellipsoid	Small to medium rounded
			Not eroded	Eroded			
Description							
	Carbonate crust covering one or several basaltic pebbles and/or rocks	Carbonate construction on big individual basaltic nucleus	Medium size columns	Medium size columns with preservation of outer part	Carbonate construction on medium size basalts	Small lumpy texture with different grades of preservation	Small smooth
	Smooth to warty	Smooth to lumpy	Lumpy	Lumpy	Smooth to lumpy	Lumpy	Smooth to lumpy
	1–10 cm thick	15 cm to more carbonate thickness around 1 m diameter	20–30 cm up	20–30 cm up	3–8 cm thick 20–30 cm diameter	From 5 to 15 cm to diameter	5–15 cm diameter
Depositional morphology	Lateral and vertical extension	Individuals spaced from few cm to m	Banks horizontal extension	Banks horizontal extension	Individuals spaced from few cm to m	Cluster or individuals spaced from few cm	Clusters or individuals spaced from few cm to m

#### 4.1.4 | Medium open flower-like

The medium open flower-like morphology is similar to the large open flower-like (Figure 2D). However, the carbonate crust is much thinner, varying from 3 to 8 cm with a diameter, including the basalt nucleus, ranging from 20 to 30 cm. The surface texture also varies from smooth to lumpy with each individual structure separated by a few centimetres to several metres. Almost all individuals of this morphological type are poorly preserved, with a clearly visible central nucleus and an incomplete carbonate cover. Most of the outcrops exhibiting these morphologies are located south of CLG at an altitude of ~821 to ~823 m on a substrate made up of basalt cobbles.

#### 4.1.5 | Small to medium ellipsoid

Small to medium ellipsoids are defined as carbonate constructions with a major axis varying from 5 to 20 cm and a lumpy texture (Figure 2F and G). They can form coalescent clusters or remain separate individuals with different sizes and morphologies distinguished due to various degrees of preservation. In contrast to the other types of buildup, they do not display a central nucleus independently of their degree of preservation. Basalt pebbles are found at the ‘base’ of the buildup and are totally covered by carbonate. These morphological types are observed in almost all outcrops covering altitudes from 821.5 to 828.5 m, especially east of CLG in areas where the topography is flatter and may be associated with areas where basalt pebbles are abundant.

#### 4.1.6 | Small to medium rounded shapes

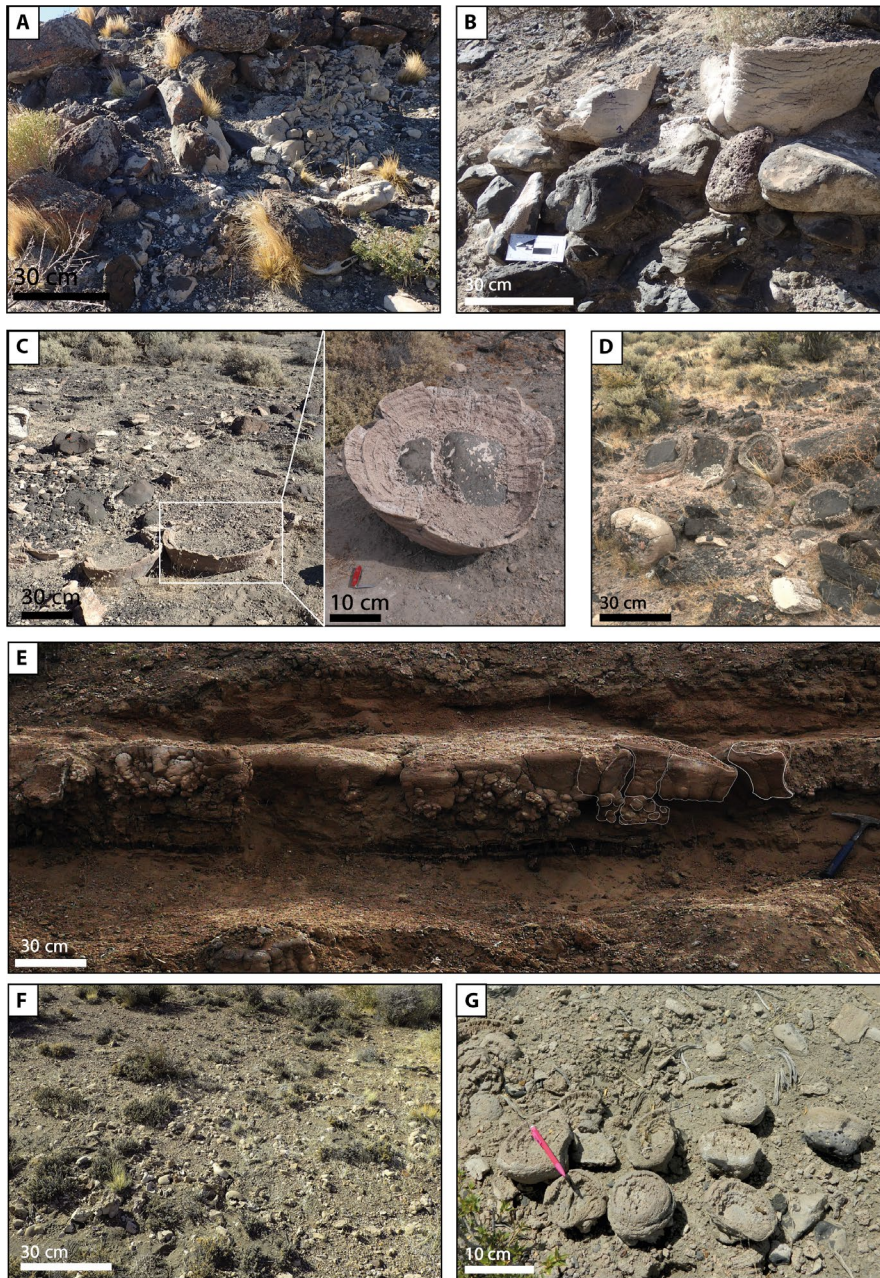
Small to medium, 5–15 cm diameter, rounded shapes with a very smooth to lumpy surficial texture also form carbonate buildups (Figure 2F and G). Discrete individuals nucleate on basalt pebbles usually fully covered by a carbonate crust. Rounded morphologies are found mostly east of CLG associated with the ellipsoidal morphologies at altitudes between 821.5 and 828.5 m where the topography is flatter. They may be associated with areas where basaltic pebbles are abundant.

In addition to the morphologies previously described, most outcrops contain broken pieces originating from non-preserved buildups although they are especially abundant in large carbonate constructions. Their size and texture are variable since they depend on the type of buildup prevailing on the site.

### 4.2 | Occurrence and distribution of the prevailing morphologies

The total altitudinal range of carbonate buildups goes from 820.8 to 830.7 m. Some of them outcrop directly on the





**FIGURE 2** Photographs of the different outcrops showing diverse morphological types. (A) Outcrop 1. Main morphology represented by crusts. (B) Outcrop 2. Large open flower-like. (C) Outcrop 3. Large open flower-like and close up on the right. (D) Outcrop 4. Medium open flower-like. (E) Outcrop 8. Column morphology, white lines delineate the outer shape. (F) Outcrop 7. Ellipsoid and rounded-like morphologies. (G) Outcrop 9. Ellipsoid and rounded-like morphologies close up

surface, generally in areas with steeper topography (Figure 3). This is the case for outcrops 1, 2 and 3 on the southern margin of CLG presenting coalescing crusts, large open flower-like and medium open flower-like buildups (Figure 3C). Outcrops with columns (sites 8 and 10) are half to totally buried under silty sediments (Figure 3A). Finally, the remaining sites are related to small or very small rounded and ellipsoid carbonate buildups with, in the case of outcrop 8, rounded and ellipsoid morphologies on top of buried columns. They mostly outcrop east of CLG, following the flatter topography (Figures 1 and 3).

There is a difference between the outcrops located above 825 m and those placed below this altitude. Most outcrops above 825 m are represented by large to medium size

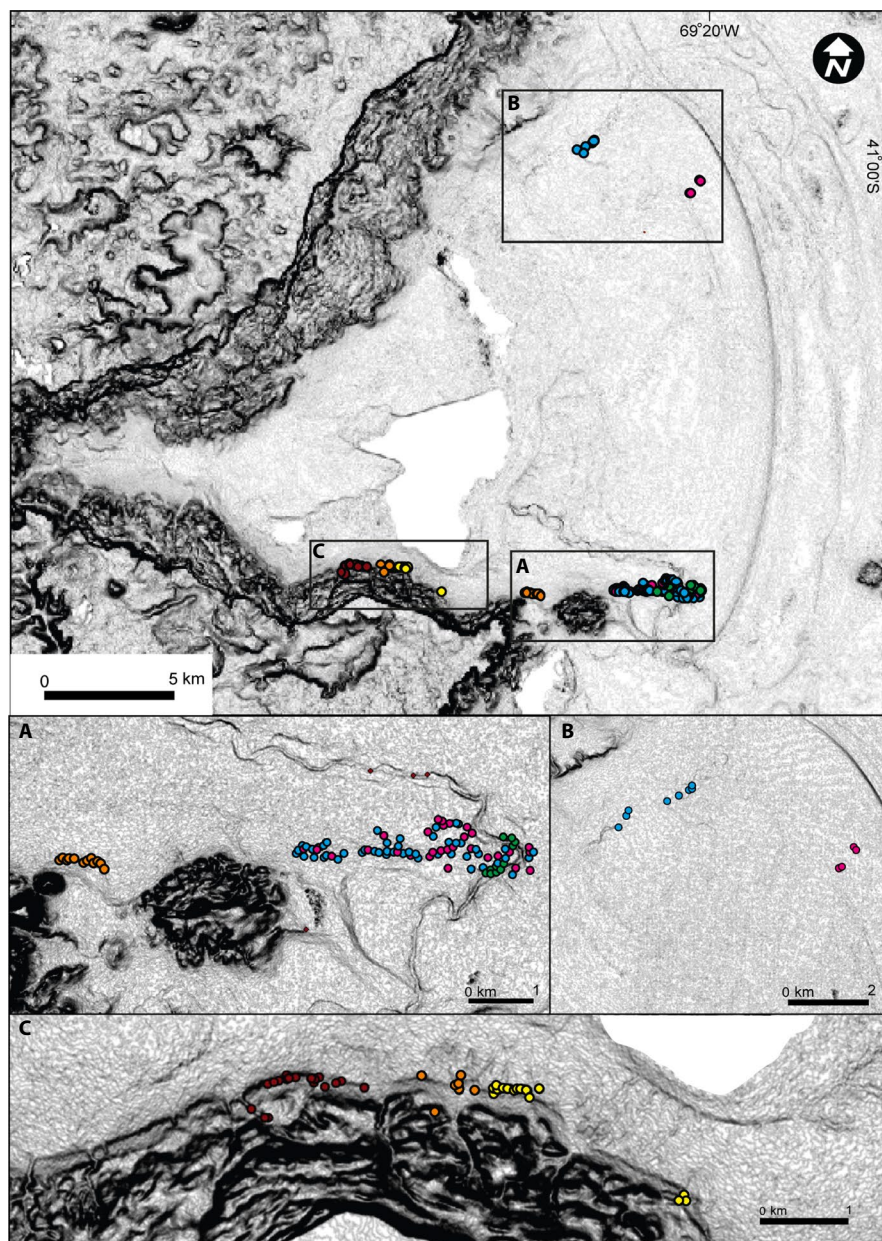
dominating carbonate fabrics and related to larger size basalt nucleus (Tables 1 and 2). Conversely, most outcrops below 825 m (especially around 824 m) comprise columnar, small rounded and ellipsoidal morphologies related to pebbles of basaltic composition (Tables 1 and 2).

#### 4.3 | Meso and micro-fabrics of carbonate buildups

The previously described morphologies display either shrub-textured (Figure 4A and B) or laminated (Figure 4B) meso-fabrics. Both textures can be found associated in a single carbonate buildup (Figure 4B). Laminations are mostly visible directly around the basaltic nucleus and on the outer

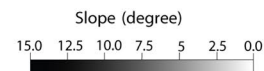


**FIGURE 3** Digital elevation map showing the slopes of Maquinchao Basin and location of the different morphological types shown in Figure 2



#### REFERENCES

- Crust
- Large open flower-like
- Medium open flower-like
- Linked columns
- Small to medium ellipsoid
- Small to medium rounded

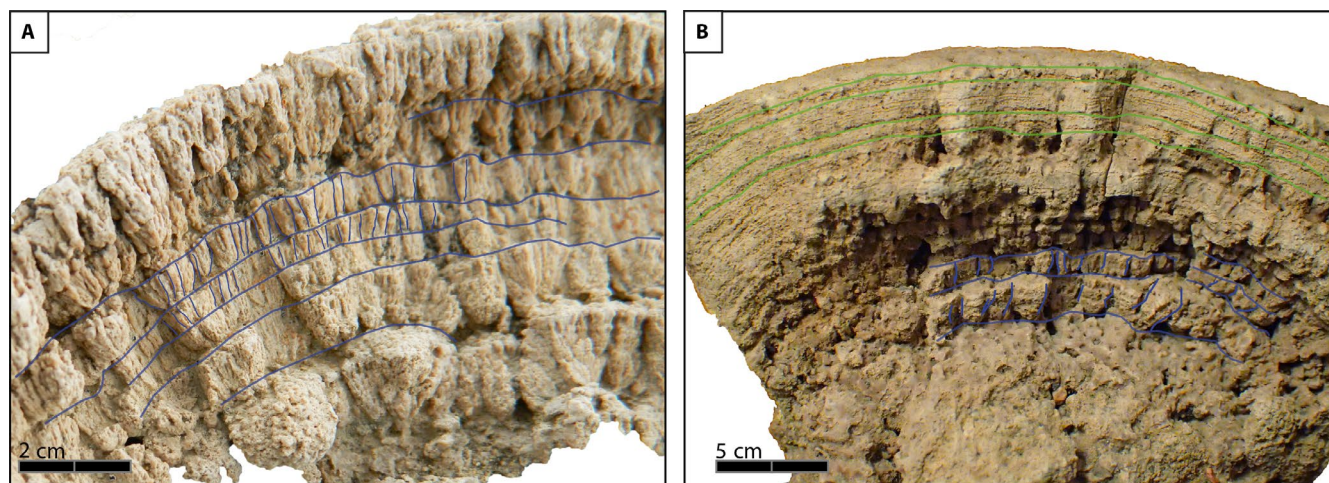


part of the carbonate constructions. Shrubs appear mostly in between the laminated layer enveloping the nucleus and the more external layer. On poorly preserved buildups, it is possible to observe how shrubs are clearly contiguous and starting on the same surface line leading to a lamination-like structure with a dominance of shrubs (Figure 4A). Outcrops 8 and 10 display a dominant shrub-like texture, whereas outcrops 1 and 3 display a larger proportion of the laminated meso-structures per buildup.

Two main microfabrics were identified through light microscopy, a laminated sparitic (Figure 5A,C and E) and a fine

filamentous micritic (Figure 5B–D and H). The first one is associated with the well-laminated meso-fabric (Figure 5A). It is mostly dominated by microsparite and has a very low porosity. The visible lamination is millimetres to centimetres-thick separated by a thinner darker layer on a millimetre scale. This facies is composed of alternating thicker microsparite layers, with a maximal elongation of the crystals and thinner darker layers of micrite (Figure 5E). Transition between both facies appears to be sharp (Figure 5C). In addition few filaments were noticed. At a microscopic scale, the fabric can have a parallel and wavy lamination, or can form small





**FIGURE 4** Mesofabrics of Maquinchao Basin. Blue lines indicate the shrubs whereas green lines highlight the parallel lamination. (A) Microbialite from outcrop 4 presenting the shrub structure. (B) Microbialite from outcrop 12 showing both fine laminations and shrubs

coalescent columns (Figure 5A and E). The second microfabric is associated with the shrub-textured meso-fabric that is predominantly micritic (Figure 5B and F). This facies is composed of a large number of filaments disposed mostly perpendicular to some kind of lamination and 5–8  $\mu\text{m}$  in diameter with some areas of microsparite (Figure 5B,G and H). Porosity is higher than in the previous facies and in less well-preserved samples filled by clay minerals (Figure 5D). Both facies contain extraclasts with quartz, feldspar and olivine crystals, nevertheless the micritic facies contains more extraclasts than the microsparitic one. Very few microfossils were observed in the sections.

The XRD and EDS analyses have confirmed that low-Mg calcite is the main mineral phase of the different morphologies and meso-structures of the buildups as previously observed by Pacton et al. (2015) in the modern stromatolites.

## 5 | DISCUSSION

### 5.1 | Controls on the growth and morphology of carbonate buildups – Comparison with other sites

#### 5.1.1 | Type and size of substrate

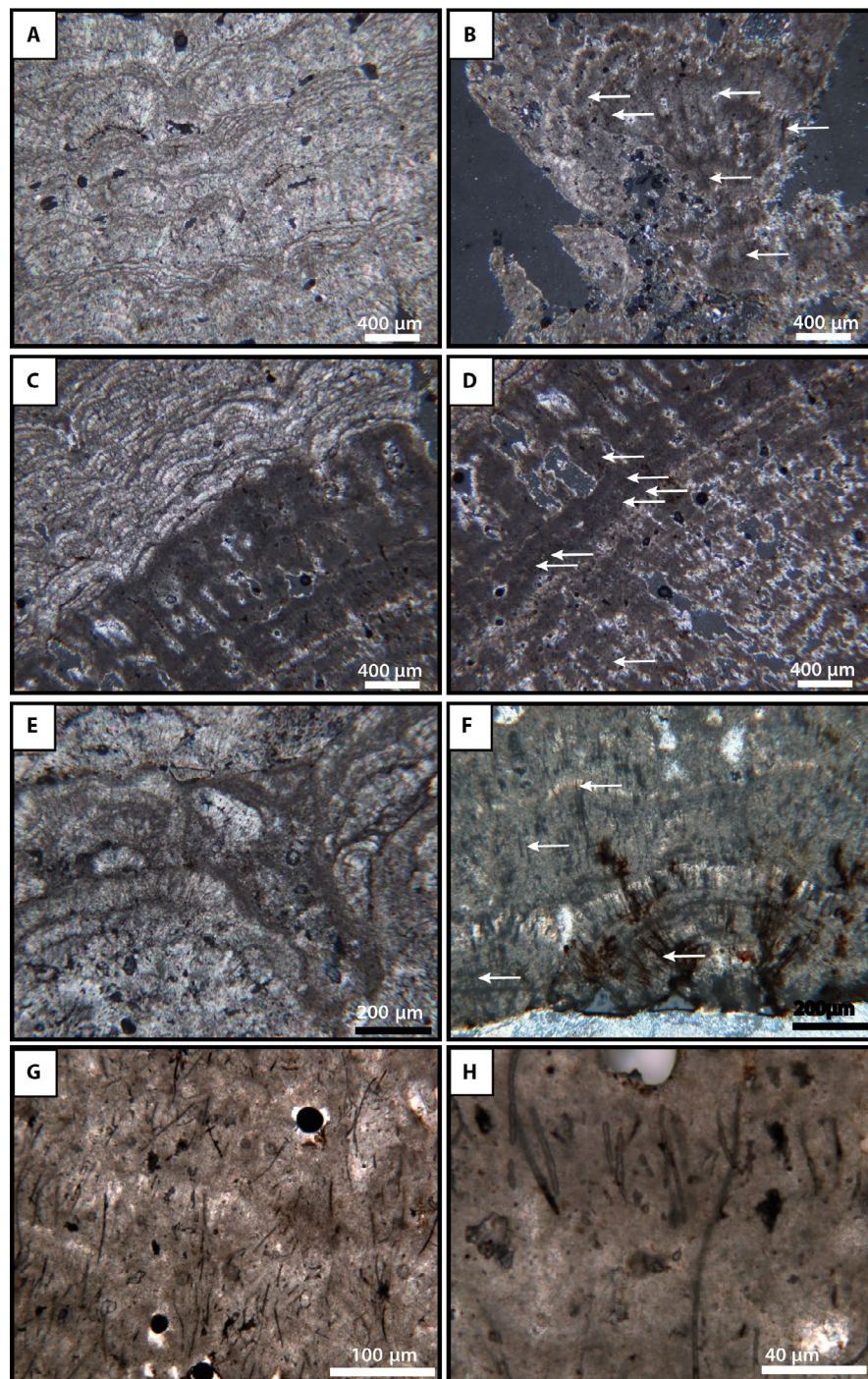
Several studies have pointed out the importance of the substrate in the formation and preservation of microbialites (Ginsburg & Planavsky, 2008; Noffke, Knoll, & Grotzinger, 2002). The geographical extension, size and morphology of the carbonate constructions of the Maquinchao Basin seem to be closely related to the distribution of the basaltic substratum. Both fossil and living microbialites are found mostly on basaltic clasts, the hardest substrate and most abundant lithology in the basin (Table 2). In most cases (flower-like, ellipsoid and rounded morphologies), carbonate buildups

occur on one unique basalt piece ranging in size from pebbles to (small) boulders (Table 1). Large open flower-like morphologies varying between 50 and 100 cm display the thickest carbonate crusts (Table 2) followed by the medium open flower-like and finally the small rounded and ellipsoids (Table 2). Columns and in a few cases the medium ellipsoidal shapes, grow over a cluster of multiple basalt pebbles of variable sizes. Finally, crusts follow the topography covering various basaltic clasts of different sizes although the larger substrates are typically preferred (cobble to boulder) (Table 2). Crusts are most of the time coalescent. Similar sized substrates, however, may produce different buildup morphologies (Table 1) pointing out the existence of additional stressors that shape the different morphotypes. Crusts are observed at the topographically highest site (Table 1) and only on the south margin of CLG (Figure 1; Table 1). Similar morphology has been related to water percolation (river-waterfall) (Pentecost, 2005) or rapid fluctuations in water level (Vennin et al., 2018). Columns and large open flower-like structures are the largest morphologies in the Maquinchao Basin displaying the thickest carbonate crust (Table 2). Nevertheless columns are found on the same type/size of substrate as rounded and ellipsoid-like buildups (Table 1). The difference between these two morphologies might be related to differences in water level, thought to have been relatively higher during column formation than when the rounded and ellipsoid morphological types formed. Thus, lake-level fluctuations appear to influence the vertical extension of the carbonate buildups independently of the size of the basaltic material at each site.

Despite the presence of basalt boulders and pebbles over the entire basin, no outcrops have been observed on the west part of CLG, around CLC, or below 815 m (Figure 1). Additionally, no living microbial mats have been spotted close to the actual flat shores of CLG and CLC despite the



**FIGURE 5** Thin section images of the different microfabrics present in the Maquinchao Basin. White arrows indicate filament structures. (A) Microsparitic microfabric with wavy laminae from outcrop 7; (B) Dense micritic microfabric with filaments from outcrop 3; (C) Laminated microsparite on top of a dense micritic zone from outcrop 3. (D) Micritic microfabric showing increasing porosity of sample from outcrop 3. (E) Close up of wavy microsparite from outcrop 4. (F) Close up of filaments embedded in dense micrite from outcrop 7. (G) Filaments in the micritic facies forming the column morphology of outcrop 8. (H) Close up microphotograph of the filaments in outcrop 8



abundant basalt pebbles (Pacton et al., 2015). It thus appears that in addition to the presence of hard basalt substrates of different sizes (Ginsburg & Planavsky, 2008) several other concurrent factors within the basin are conditioning the distribution and development of these carbonate buildups.

### 5.1.2 | Springs/groundwater input

Living microbialites have been observed primarily in extreme environments (hypersaline, high UV, high temperature environment). Results of recent studies indicate that in

addition to water level and shorelines, the impact of other parameters such as spring water input (Farías et al., 2013), combined with a particular tectonic setting (Bouton et al., 2016) or the presence of restricted areas for water circulation, control the distribution of microbialites. There is a lack of microbialites in both modern lakes CLG and CLC whereas they are present in the meandering sections of the Maquinchao River. Ongoing investigations regarding the hydrology of the Maquinchao Basin (Alvarez, Carol, Eymard, Bilmes, & Ariztegui, 2018) show that the conditions of low turbidity and compositional stability where the microbialites

occur are due to a particular configuration of the basin and constant groundwater flow. In addition, the low turbidity could also result from the CLC acting as a 'sediment trap' and preventing sediment particles from reaching the meandering section of the Maquinchao River. On the other hand, the chemical composition of the meander waters is not only lower salinity than CLC and CLG but also seasonally stable over the five sampling campaigns. The Maquinchao River receives inflow from groundwater along the upgradient margin and discharges flow to groundwater along the downgradient margin maintaining a more stable chemical composition than the lakes that are exposed to strong evaporation.

Pacton et al. (2015) have discovered living microbial mats containing low-Mg calcite, the same mineralogy as in the fossil carbonate buildups. They are only present in the Maquinchao River and absent in both lakes. The modern distribution of the microbial mats has been related to the different water chemistry between both lakes and the Maquinchao River as shown by the results of a sampling campaign during the austral summer. The CLG is a saline alkaline lake (pH: 9.2–9.4; Salinity 13‰) and CLC is brackish with high pH (pH: 8.5–9.4; Salinity 1.3–6‰), whereas the freshwater Maquinchao River has a very different chemical composition (pH: 8.1, salinity: 0.7‰) (Pacton et al., 2015; figure 5). Additionally, Pacton et al. (2015) report higher concentrations of Na in CLG (4,750 ppm) compared to CLC (around 1,000 ppm) and the Maquinchao River (150 ppm), while the Ca concentrations in Maquinchao River (42 ppm) are higher than CLC and CLG values (approximately 7–9 ppm). These differences in composition, first measured in 2011, have been confirmed by seasonal sampling from 2015 to 2018 (Alvarez et al., 2018; Pascuale Pérez et al., 2019). The strong salinity of CLG might be preventing the abiotic precipitation of carbonate while being less attractive to the development of microbial mats. Furthermore, the comparatively low Ca concentration in CLC and CLG when compared to the Maquinchao River might also preclude carbonate precipitation. It has been proposed that the influx of water rich in Ca in an alkaline water body is the key element to start carbonate precipitation (Demott, Scholz, & Junium, 2019; Dunn, 1953; Kaźmierczak et al., 2011). In the Maquinchao Basin, however, the actual flux of the Maquinchao River into CLG does not appear to trigger precipitation of any sort of carbonate buildup. On the CLC northern shore a thin carbonate coating has been observed on pebbles although there is no sign of carbonate buildups accreting. Therefore, it appears that at present chemistry alone cannot explain the formation of the Maquinchao carbonate buildups. It favours the hypothesis that groundwater input together with stable lake water conditions might have a pivotal influence in the initial development of microbialites that appear to grow in areas of mixed, less saline waters (i.e. brackish to freshwater; Pacton et al., 2015). Furthermore, during the former Maquinchao

Lake high-stand that characterized the last deglaciation (Cartwright et al., 2011; Galloway et al., 1988) the chemistry of the water was most probably less saline than today and closer to the actual Maquinchao River chemistry allowing preferential conditions for the growth of carbonate buildups (Pacton et al., 2015).

### 5.1.3 | Topography

The distribution of the different morphologies seems to be at least partially related to the distribution of the substratum, which in turn is most probably related to the original topography of the Maquinchao Basin.

Two main types of sites for carbonate formation can be identified: flat extended areas east of CLG (including outcrops 4, 5, 6, 7, 11, 12, 13 and 14) and areas of strong vertical steepness located directly south of CLG (Figure 3). The first one, of large lateral extension, is found in areas with a very low gradient. Associated morphologies are defined by the prevailing pebble size of the basaltic substratum (Table 2) and by the number of buildups. This kind of environment could be similar (even if at smaller scale) to protected restricted areas in large lakes or marine lagoons containing stromatolites such as Great Salt Lake (USA), The Bahamas and Shark Bay (Australia), or very shallow lakes in the high Argentinean and Chilean Altiplano (Fariás et al., 2013; Jahnert & Collins, 2012; Reid, Macintyre, Browne, Steneck, & Miller, 1995; Vennin et al., 2018). In the sites located on a steeper slope, microbialites are formed over a larger variety of basaltic clast sizes, even if the majority are cobble to boulder size (Table 2). Nevertheless, the size of the area covered by microbialites in these sites appears to be smaller than for those in the east where the topography is substantially flattened. Vennin et al. (2018) have proposed that steep slopes reduce the potential extension of photosensitive microbialites. However, the crust following the morphology (i.e. the steepness of the terrain) without smoothing it seems to have more in common with the dense coated basalts described in Lake Bonneville (Bouton et al., 2016; Vennin et al., 2018) and Walker Lake (Benson, 1993). These coated basalts having a thinner but dense carbonate outer layer have been described as a record of both the highest and the lowest water levels of Lake Lahontan and Lake Bonneville (Benson, 1993; Bouton et al., 2016; Vennin et al., 2018) and record a non-stable water level. Thus, low gradient areas promote the growth of microbialites compared to steeper areas in the Maquinchao Basin. In addition, non-turbid conditions are mandatory for the substantial growth of microbialites. This indicates that "protected" areas probably distant from sediment sources or other highly turbid zones affected by strong currents, such as the centre of the Maquinchao Basin, are more appropriate for the development of carbonate buildups. An additional parameter conditioning the distribution of larger outcrops on flatter, protected areas,



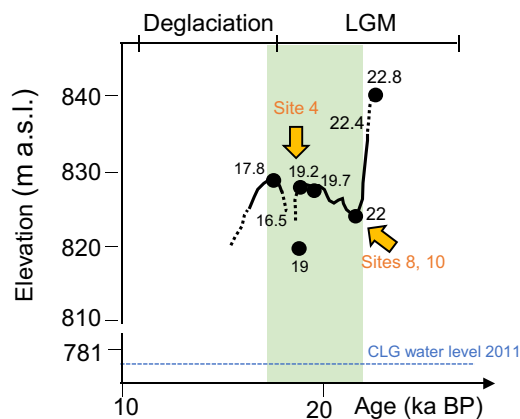
might be the lateral distribution of groundwater or freshwater inputs on a low gradient topography. Conversely, on shores with a higher topographical gradient these lateral extensions would be substantially restricted, a conclusion confirmed by Alvarez et al. (2018) using hydrological and geomorphological arguments, respectively. These facts would explain the preferential distribution of the carbonate buildups mostly located south, southeast and northeast of CLG.

#### 5.1.4 | Lake-level changes

Many studies in lacustrine settings have used biogenic stromatolites to estimate former coastlines and/or to reconstruct palaeobathymetry (Casanova & Hillaire-Marcel, 1993; Roche et al., 2018). More generally, microbialites and particularly stromatolites are associated with lake margins, by generating belts subparallel to the shoreline down to 10 m water depth (Della Porta, 2015). In most cases, they predominantly host photosynthetic communities in the first layer (microbial and/or metazoan and/or algal) and thus, are highly dependent on luminosity, water level and turbidity (Della Porta, 2015 and references therein). In the Maquinchao Basin, clear palaeoshorelines on the east coast of CLG are visible in satellite images as previously mentioned by Cartwright et al. (2011) and earlier described by Bradbury et al. (2001) and Galloway et al. (1988). The highest and therefore predicted oldest palaeoshorelines are between 839 and 842 m (current road level) and 844 and 848 m representing the highest water level of the former Maquinchao large lake (Bradbury et al., 2001; Cusminsky et al., 2011). Several studies have previously attempted to date them, providing ages between 25 and 29 ka BP for the lowest one and over 40 ka for the highest one (Cartwright et al., 2011). Additionally, a few dates have been obtained from some carbonate buildups located south-east of CLG providing ages varying from 19.2 ka BP for samples coming from outcrop 4 (Figure 1) to 22.2 ka BP for the lowest part of outcrop 8 (Figure 1) (Cartwright et al., 2011; Galloway et al., 1988). Moderate lake-level fluctuations over the last 15 years have been identified using modern satellite images but there is no evidence of carbonate buildups at those altitudes (Figure 1). The carbonate buildups are located only between 820 and 830 m (Figure 1), with a major concentration around 825 m. The lack of carbonate constructions at most palaeoshorelines indicates that the best conditions for carbonate precipitation and buildup formation were only fulfilled during a reduced period of the Maquinchao Basin history. This highlights that major changes in extrinsic parameters, particularly those related to the Maquinchao lake water level and associated chemistry, probably occurred.

In the Maquinchao Basin, it appears that columns represent the largest structure in terms of carbonate precipitation followed by the large open-flowers type at altitudes of 823 to 825 m and 825 to 827 m, respectively (Table 1; Figure

3). Conversely, the highest outcrops between 826 and 831 m are crusts representing the thinnest carbonate morphologies (Table 2). Vennin et al. (2018) and Roche et al. (2018) have suggested that in Lake Bonneville the thickest microbialites, comparable to the columns and large flower-like morphologies of the Maquinchao Basin, could have formed during high and stable lake water levels. Vennin et al. (2018) concluded that Lake Bonneville water-level fluctuations had a strong impact on the type and morphology of the carbonate buildups. Hence, the formation of carbonate buildups depends directly on the stability of the water level if both extrinsic and intrinsic parameters are suitable. Stable water conditions would be further accompanied by low energy and turbidity in the water column that would, in turn, allow better development of microbialites. Conversely, crusts would record formerly unstable conditions in the water levels of the Maquinchao large lake. Furthermore, they could be associated with a short high stand period followed by a lake regression. In the light of the collected data (Table 1) it is possible to identify three progradation events of the large Lake Maquinchao that are preserved between 820 and 830 m (Figure 6). A first rise stabilizing above 824 m with the formation of columnar morphologies was followed by a second rise and stabilization above 827 m associated with the large open-flower morphologies. Finally, there was a short rise, probably with fluctuations leading to the crust morphology. Conversely, rounded, ellipsoid and medium open flower-like morphologies would be related to a less stable phase of continuous lake regression. The latter is confirmed by the presence of rounded and ellipsoid buildups outcropping above buried columns (Figure 2E) most probably associated with a regression leading to the modern system encompassing the two lakes (CLG and CLC). Alternatively, the presence of different macro-morphotypes



**FIGURE 6** Reconstructed lake-level curve of the palaeolake Maquinchao (modified from Hunger, 2012). Black dots indicate ages after Bradbury et al. (2001), Cartwright et al. (2011) and Tatur et al. (2002). Pointed line indicates CLG water level in 2011. Green shaded area shows the time interval enclosing the formation of carbonate buildups and orange arrows the outcrop sites as in Figure 1

in the Maquinchao Basin could be related to a depth gradient and micro-changes in chemistry for the same lake stand. However, the step-wise climate amelioration that characterized the area during deglaciation would favour several pulses of lake-level changes (i.e. Ariztegui et al., 2001).

Several studies on sedimentary cores retrieved in present lakes CLG and CLC have been used to reconstruct changes in water salinity throughout time by using variations in the dominant assemblages of microorganisms (Bradbury et al., 2001; Coviaga et al., 2018; Cusminsky et al., 2011; Schwalb et al., 2002; Whatley & Cusminsky, 1999). These studies have been carried out on different cores and outcrops covering estimated ages from 13.0 ka BP to the present. These records show a relatively low abundance of diatoms and a larger abundance and diversity of ostracods with *Limnocythere rionegroensis* as the dominant species, suggesting a turbid and possible saline lake. Several phases of increasing diversity in ostracod species indicate a probable decline in lake salinity and a higher lake level (Bradbury et al., 2001; Coviaga et al., 2018; Cusminsky et al., 2011). Unfortunately, these records are younger than the existing ages for the Maquinchao microbialites (Figure 6 and Cartwright et al., 2011) or have uncertain ages (Whatley & Cusminsky, 1999) preventing a direct comparison. Nevertheless, an examination of thin sections indicates a prevailing lack of microfossils (Figure 5) in agreement with the observations of the younger Lake Maquinchao suggesting low productivity in the lake during the Late Pleistocene and the Holocene.

## 5.2 | Biotic versus abiotic processes

The mineralogy of microbialites is mostly driven by water chemistry, and to some extent by physical parameters such as temperature. The composition of stromatolites is quite variable, including dolomite, calcite and gypsum, whereas the lamina encompasses allochthonous material as a result of trapping and binding by microbial mats (Riding, 2011b). Additionally, microbial microfossils can be preserved if they have not been affected by pervasive diagenesis. In the Maquinchao Basin, the mineralogy of all buildups is very homogeneous with a dominant low-Mg calcite composition and a minor contribution from clays, olivine and feldspar without notable differences between outcrops and morphotypes. The presence of microfossils is very low to absent. This has been previously observed by Bradbury et al. (2001); Coviaga et al. (2018); Cusminsky et al. (2011); Schwalb et al. (2002); Whatley and Cusminsky (1999) who all show a lack of well-preserved diatoms and a relative paucity of ostracod assemblages. Paction et al. (2015) in their study of modern microbial mats further observed dissolution patterns in diatom frustules. Various investigations have already demonstrated the dissolution of diatom frustules in saline, carbonate-rich water bodies as well as shallow lakes (Ryves, Battarbee,

Juggins, Fritz, & Anderson, 2006). Thus, the absence of microfossils in the Maquinchao samples is most probably due to a combination of relatively low productivity and a lack of preservation.

Most of the carbonate buildups, despite their difference in macro-morphologies, present both laminated and shrub-like mesofabrics and the associated laminated microspar and micritic microfabrics. Site 1 is the only outcrop presenting a larger proportion of laminated meso and microfabrics compared to the meso shrub-like and the micrite microfabric. Investigations at other sites have shown that microbialites can display microfabrics typical of encrusting or coated eukaryotes (Pentecost, 2005; Roche et al., 2018). Although the carbonate buildups of the Maquinchao Basin do not show such structures they display abundant filament-like structures associated with micrite (Figure 5B). Filaments of around 5–10 µm width have been identified as different microorganisms, mostly cyanobacteria such as *Oscillatoria*, *Phormidium*, *Schizothrix* or *Rivularia*, especially in fluvial and lacustrine systems (Freytet & Plet, 1996; Freytet & Verrecchia, 1998). Nevertheless, Kraus, Beeler, Mors, Floyd, and Stamps (2018) has demonstrated that vertical tubular porosity can be associated with micro-boring by microorganisms. Although associated with micrite, filament-like porosity in the Maquinchao samples seems to be unrelated to porosity. Furthermore, micro-boring organisms can be a source of micritization (Bathurst, 1966; Kraus et al., 2018) but this does not appear to be the case in this study as the micrite is very homogeneous and, therefore, unlikely to result from micro-boring. In the analysed samples, filaments were observed that are mostly vertically erected with no ramifications. This is similar to *Phormidium* and other *Oscillatoria*, also associated with low-Mg calcite 5–8 µm in width (Freytet & Verrecchia, 1998; Golubic & Fischer, 1975; Pentecost, 2005) and capable of growing perpendicular to the substrate in quiet—low currents—fluvial and lacustrine environments. The identification of these microorganisms is always challenging in non-active systems, and therefore it is not possible to assess the species. Nevertheless, the best candidate is most probably a filamentous erected cyanobacteria. Furthermore, micrite in a similar environment has been previously related to microbial life by the uptake of  $\text{HCO}_3^-$  during photosynthesis (Merz-Preiß & Riding, 1999). This would support a certain biological influence in the formation of Maquinchao carbonate buildups. However, the homogeneity of the mineral phase, the low Mg-calcite mineralogy, and the lack of diversity in micro-facies for the six different morphologies and outcrops would suggest that extrinsic factors ruling the water chemistry of the lake might have a substantial impact on the formation of these carbonate buildups. In fact, the laminated meso-structures associated with the microsparitic facies do not present as much filament-like structure as the micritic facies (Figure 5). Several studies have suggested

that sparry and micro-sparry calcite are the result of accelerated crystallization due to CO<sub>2</sub> degassing (Gradziński, 2010; Merz-Preiß & Riding, 1999). The latter is observed in fluvial and lacustrine environments supporting an abiotic fabric where no microbial life is needed for carbonate precipitation. Nevertheless, according to Freytet and Verrecchia (1998), the absence of organic traces in sparite and microsparite fabrics does not necessarily imply the absence of a biological influence. Indeed, diagenetic processes would allow for recrystallization of the initial micrite into microsparite and/or sparite removing any microbial traces (Freytet & Verrecchia, 1998, 1999). The latter scenario makes it difficult to disentangle physico-chemical lamination over diagenetic changes. Thus, the formation of Pleistocene carbonate buildups in the Maquinchao Basin appears to be due to a combination of organomineralization s.l. (Dupraz et al., 2009) and possibly inorganic mineralization.

Freshwater carbonates due to passive organomineralization (tufa/travertine/non-biotic stromatolite) are even more closely related to a specific water chemistry and CO<sub>2</sub> degassing. In this case, the meso and macro-morphologies of carbonate constructions can be attributed to extrinsic parameters, providing critical information regarding the water chemistry and water energy of the precipitating system, for example, such as whether it was fed by a river or underground water. The best examples of this kind of phenomena have been observed in several lakes of northwestern North America such as the pinnacles, columns or towers of Mono Lake, Lake Alchichica and Lake Van (Brasier et al., 2018; Kaźmierczak et al., 2011; Kempe et al., 1991), or the tubular and massive domes of former Lake Lahontan (Benson, 1994; Demott et al., 2019). The morphologies and extension of these structures are reported as linked to underground water input in a bottom lake. The latter can mask the plausible correlation between those morphologies and changes in water level (Demott et al., 2019). Other mega-morphologies affiliated with tufa/travertine have been reported elsewhere (Della Porta, 2015; Pentecost & Viles, 1994) and described as spring mounds, cascade, barrage, fluvial or lacustrine crust and paludal deposits. Some of these morphologies are directly linked to an abiotic source of CO<sub>2</sub>. As compiled and confirmed in Della Porta (2015) even when acting as an apparently passive substrate, microbial communities are a key component of these complex constructions resulting from mixing between physicochemical and organic components. Neither the specific columnar or tower shapes with central porosity as in former Lake Lahontan or Mono Lake have been observed nor the very specific fluvial shapes such as dams or ridges. The morphologies observed at the Maquinchao Basin are mostly ellipsoid, rounded or columnar shapes (Table 1), smaller in size than those described at other sites.

Ginsburg (1991), in his paper about the Vices and Virtues of stromatolites (1991), pointed out the difficulty

in interpreting these structures due to the dueling influence of both abiotic and biotic factors and the difference in microstructures between old and modern forms. Pacton et al. (2015) has described the presence of living microbial mats in freshwater sections of the present Maquinchao Basin and proposed the carbonate buildups as possible fossil counterparts. The study pointed out the presence of low-Mg calcite precipitates within microbial mats composed of filamentous and coccoid cyanobacteria as a result of organomineralization process and growth on basaltic pebbles. They show similarities in the globular macro-morphologies between living forms and carbonate buildups from around 22 ka BP (fig. 2 in Pacton et al., 2015). Both modern and fossil specimens share the same mineralogy, the presence of filament-like structures and a basaltic nucleus. The lack of completely mineralized modern microbial mats makes a detailed comparison of modern and fossil microstructures impossible and, thus, it is difficult to fully assess the hypothesis proposed by Pacton et al. (2015). Nevertheless, the observation of the substratum, mineralogy, microfauna and restricted areas of growth point towards similarities between modern and Pleistocene occurrences. Therefore, the documented modern physico-chemical conditions of microbial mat formation are most probably quite similar to those during the formation of the Pleistocene carbonate buildups.

Although still incomplete, such observations provide numerous indications that microbial processes have been involved in the formation of the Maquinchao carbonate buildups. Burne and Moore (1987) describe microbialites as ‘organosedimentary deposits that have accreted as a result of a benthic microbial community trapping and binding detrital sediments and/or forming the locus of mineral precipitation’. Thus, according to this definition the carbonate buildups of the Maquinchao Basin can be defined as microbialites and even as stromatolites following the genetic definition. However, further investigations are necessary to disentangle biotic and abiotic processes and more generally differentiate induced and/or influenced organomineralization (s.l.) processes in their formation.

## 6 | CONCLUSIONS

The Maquinchao Basin presents some similarities with other Pleistocene lakes such as Bonneville and Lahontan in northwestern America. All these large water bodies have had major lake-level variations as a result of climate change during the last deglaciation. They further share the presence of atypical carbonate constructions. No matter the size of the basin the distribution of outcrops appear to be closely related to extrinsic stressors such as geomorphology/tectonics and hydrology. Nevertheless, extrinsic and physicochemical conditions are not the only parameters controlling the formation of



carbonate. It also appears that microorganisms have played an active role in their formation. Because these Pleistocene microbialites are associated with photosynthetic microorganisms they are also relevant for the study of lake-level variations. Their morphology appears to be regulated mostly by extrinsic parameters of the water column such as the energy/currents and bathymetry, but also the type of substrate as well as the slope of the basin. Most of these components are driven by climate. Therefore, microbialites provide us with a unique tool for palaeoclimate reconstructions. In the Maquinchao Basin lake-level fluctuations reconstructed using microbialites would include a phase of lake-level progradation and stabilization above a minimum altitude of 824 m and the formation of columnar type buildups. A second rise of water level reaching another stable level triggered the formation of large open-flower morphotypes. A third rise appears to be short and probably with some fluctuations, accompanied by the formation of crust morphologies. The columns have been totally buried by fine sediments whereas the large flower-like buildups have been only partially covered. The continuous regression of the Maquinchao lake leads to the formation of ellipsoids and rounded like microbialites.

These results have shown that the Maquinchao microbial buildups are a valuable proxy for water level evolution and therefore palaeoenvironmental reconstructions. They can be also used to seek the causes behind the apparently random distribution of morphological types and extension of microbialites in the geological past. As suggested by Bob Ginsburg this data further indicates that microbes appear to determine microstructure whereas the environment shapes morphology. Since these two processes are also closely coupled at both micro and macro scales it is difficult to disentangle them and the magnitude of this involvement remains the subject of future investigations.

## ACKNOWLEDGEMENTS

This work was funded by the Swiss National Science Foundation projects number 200021\_155927 and 200021\_15592772 to D.A. We thank Prof. Gabriela Cusminsky (INIBIOMA CONICET, Argentina) for help during fieldwork and Drs Suzanne Schmidt and Annette Süssenberger (University of Geneva, Switzerland) for XRD analyses. François Gischig is also acknowledged for technical assistance and thin-sections preparation. We acknowledge the comments and suggestions of two anonymous reviewers that improved an earlier version of the manuscript.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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## REFERENCES

- Agosta, E., Compagnucci, R., & Ariztegui, D. (2015). Precipitation linked to Atlantic moisture transport: Clues to interpret Patagonian palaeoclimate. *Climate Research*, 62(3), 219–240. <https://doi.org/10.3354/cr01272>.
- Alvarez, M. P., Carol, E., Eymard, I., Bilmes, A., & Ariztegui, D. (2018). El agua subterránea como factor fundamental para el desarrollo de estromatolitos de agua dulce en la Patagonia extraandina. In García, R. F., Castro, E., Auge, M., Falcón, C., Blarasín, M. (Eds.), *El Agua Subterránea: Recurso sin Fronteras*. Salta, República Argentina: Editorial de la Universidad Nacional de Salta. CD-ROM, DOCX. ISBN 978-987-633-538-6.
- Andrews, J. E., & Brasier, A. T. (2005). Seasonal records of climatic change in annually laminated tufas: Short review and future prospects. *Journal of Quaternary Science*, 20(5), 411–421. <https://doi.org/10.1002/jqs.942>.
- Ariztegui, D., Anselmetti, F., Gilli, A., & Waldmann, N. (2008). Late Pleistocene environmental changes in Patagonia and Tierra del Fuego – A limnogeological approach. In J. Rabassa (Ed.), *The Late Cenozoic of Patagonia and Tierra del Fuego* (vol. 11, pp. 241–253). Developments in Quaternary Sciences. Elsevier Amsterdam, The Netherlands. [https://doi.org/10.1016/S1571-0866\(07\)10011-7](https://doi.org/10.1016/S1571-0866(07)10011-7).
- Ariztegui, D., Anselmetti, F. S., Kelts, K., Seltzer, G. O., & D'Agostino, K. (2001). Chapter 14 – Identifying Paleoenvironmental change across South and North America using high-resolution seismic stratigraphy in lakes. In V. Markgraf (Ed.), *Interhemispheric climate linkages* (pp. 227–240). San Diego, CA: Academic Press. <https://doi.org/10.1016/B978-012472670-3/50017-3>.
- Bathurst, R. G. C. (1966). Boring algae, micrite envelopes and lithification of molluscan biosparites. *Geological Journal*, 5(1), 15–32. <https://doi.org/10.1002/gj.3350050104>.
- Benson, L. (1993). Factors affecting  $^{14}\text{C}$  ages of lacustrine carbonates: Timing and duration of the last Highstand lake in the Lahontan Basin. *Quaternary Research*, 39(2), 163–174. <https://doi.org/10.1006/qres.1993.1020>.
- Benson, L. (1994). Carbonate deposition, Pyramid Lake subbasin, Nevada: 1. Sequence of formation and elevational distribution of carbonate deposits (Tufas). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 109(1), 55–87. [https://doi.org/10.1016/0031-0182\(94\)90118-X](https://doi.org/10.1016/0031-0182(94)90118-X).
- Bouton, A., Vennin, E., Boule, J., Pace, A., Bourillot, R., Thomazo, C., ... Visscher, P. T. (2016). Linking the distribution of microbial deposits from the Great Salt Lake (Utah, USA) to tectonic and climatic processes. *Biogeosciences*, 13(19), 5511–5526. <https://doi.org/10.5194/bg-13-5511-2016>.
- Bradbury, J. P., Grosjean, M., Stine, S., & Sylvestre, F. (2001). Chapter 16 – Full and Late glacial lake records along the PEP 1 transect: Their role in developing interhemispheric Paleoclimate interactions. In V. Markgraf (Ed.), *Interhemispheric climate linkages* (pp. 265–291). San Diego, CA: Academic Press. <https://doi.org/10.1016/B978-012472670-3/50019-7>.
- Brasier, A., Wacey, D., Rogerson, M., Guagliardo, P., Saunders, M., Kellner, S., ... Reijmer, J. (2018). A microbial role in the

- construction of Mono Lake carbonate chimneys? *Geobiology*, 16(5), 540–555. <https://doi.org/10.1111/gbi.12292>.
- Burne, R. V., & Moore, L. S. (1987). Microbialites: Organosedimentary deposits of benthic microbial communities. *Palaaios*, 2(3), 241. <https://doi.org/10.2307/3514674>.
- Cartwright, A., Quade, J., Stine, S., Adams, K. D., Broecker, W., & Cheng, H. (2011). Chronostratigraphy and lake-level changes of Laguna Cari-Laufquén, Río Negro, Argentina. *Quaternary Research*, 76(3), 430–440. <https://doi.org/10.1016/j.yqres.2011.07.002>.
- Casanova, J., & Hillaire-Marcel, C. (1993). Carbon and oxygen isotopes in African lacustrine stromatolites: palaeohydrological interpretation. In P. K. Swart, K. C. Lohmann, J. McKenzie, & S. Savin (Eds.) *Climate change in continental isotopic records* (Vol. 78, 123–133). Geophysical Monograph. Washington, DC: American Geophysical Union. <https://doi.org/10.1029/GM078p0123>.
- Coira, B. L. (1979). Descripción geológica de la hoja 40 d Ingeniero Jacobacci. *Boletín Servicio Geológico Nacional*, 168, 101 pp.
- Couradeau, E., Benzerara, K., Gérard, E., Esteve, I., Moreira, D., Tavera, R., ... López-García, P. (2013). Cyanobacterial calcification in modern microbialites at the submicrometer scale. *Biogeosciences*, 10(8), 5255–5266.
- Coviaga, C., Cusminsky, G., Pérez, A. P., Schwalb, A., Markgraf, V., & Ariztegui, D. (2018). Paleoenvironmental changes during the last 3000 years in Lake Cari-Laufquen (Northern Patagonia, Argentina), inferred from ostracod paleoecology, petrophysical, sedimentological and geochemical data. *The Holocene*, 28(12), 1881–1893. <https://doi.org/10.1177/0959683618798131>.
- Cusminsky, G., Schwalb, A., Perez, A. P., Pineda, D., Viehberg, F., Whitley, R., ... Anselmetti, F. S. (2011). Late quaternary environmental changes in Patagonia as inferred from lacustrine fossil and extant ostracods. *Biological Journal of the Linnean Society*, 103(2), 397–408.
- Della Porta, G. D. (2015). Carbonate build-ups in lacustrine, hydrothermal and fluvial settings: Comparing depositional geometry, fabric types and geochemical signature. *Geological Society, London, Special Publications*, 418, 17–68. <https://doi.org/10.1144/SP418.4>.
- Demott, L. M., Scholz, C. A., & Junium, C. K. (2019). 8200-year growth history of a Lahontan-age lacustrine tufa deposit. *Sedimentology*. <https://doi.org/10.1111/sed.12579>.
- Departamento Provincial de Aguas (DPA). (2012). Informe Lagunas Carri-Laufquen. DPA, Provincia de Río Negro, Argentina. Retrieved from <http://www.dpa.gov.ar>
- Dunn, J. R. (1953). The origin of the deposits of tufa in Mono Lake [California]. *Journal of Sedimentary Research*, 23(1), 18–23. <https://doi.org/10.1306/D4269530-2B26-11D7-8648000102C1865D>.
- Dupraz, C., Reid, R. P., Braissant, O., Decho, A. W., Norman, R. S., & Visscher, P. T. (2009). Processes of carbonate precipitation in modern microbial mats. *Earth-Science Reviews*, 96(3), 141–162. <https://doi.org/10.1016/j.earscirev.2008.10.005>.
- Farías, M. E., Rascovan, N., Toneatti, D. M., Albarracín, V. H., Flores, M. R., Poiré, D. G., ... Polerecky, L. (2013). The discovery of stromatolites developing at 3570 m above sea level in a high-altitude volcanic lake Socompa, Argentinean Andes. *PLoS ONE*, 8(1), e53497. <https://doi.org/10.1371/journal.pone.0053497>.
- Ford, T. D. and Pedley, H. M. (1996). A review of tufa and travertine deposits of the world. *Earth-Science Reviews*, 41(3–4), 117–175. [https://doi.org/10.1016/S0012-8252\(96\)00030-X](https://doi.org/10.1016/S0012-8252(96)00030-X).
- Frantz, C. M., Petryshyn, V. A., Marengo, P. J., Tripathi, A., Berelson, W. M. and Corsetti, F. A. (2014). Dramatic local environmental change during the Early Eocene Climatic Optimum detected using high resolution chemical analyses of Green River Formation stromatolites. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 405, 1–15. <https://doi.org/10.1016/j.palaeo.2014.04.001>.
- Freytet, P., & Plet, A. (1996). Modern freshwater microbial carbonates: The Phormidium stromatolites (tufatravertine) of southeastern Burgundy (Paris Basin, France). *Facies*, 34(1), 219–237. <https://doi.org/10.1007/BF02546166>.
- Freytet, P., & Verrecchia, E. P. (1998). Freshwater organisms that build stromatolites: A synopsis of biocrystallization by prokaryotic and eukaryotic algae. *Sedimentology*, 45(3), 535–563. <https://doi.org/10.1046/j.1365-3091.1998.00155.x>.
- Freytet, P., & Verrecchia, E. P. (1999). Calcitic radial palisadic fabric in freshwater stromatolites: Diagenetic and recrystallized feature or physicochemical sinter crust? *Sedimentary Geology*, 126(1), 97–102. [https://doi.org/10.1016/S0037-0738\(99\)00034-2](https://doi.org/10.1016/S0037-0738(99)00034-2).
- Galloway, R. W., Markgraf, V., & Bradbury, J. P. (1988). Dating shorelines of lakes in Patagonia, Argentina. *Journal of South American Earth Sciences*, 1(2), 195–198.
- Ginsburg, R. N. (1991). Controversies about stromatolites: Vices and virtues. In D. W. Müller, J. A. McKenzie, & H. Weissert (Eds.), *Controversies in modern geology* (pp. 25–36). London, UK: Academic Press.
- Ginsburg, R. N., & Planavsky, N. J. (2008). Diversity of Bahamian microbialite substrates. In Y. Dilek, H. Furnes, & K. Muehlenbachs (Eds.) *Links between geological processes, microbial activities & evolution of life: Microbes and geology* (pp. 177–195). Dordrecht, The Netherlands: Springer. [https://doi.org/10.1007/978-1-4020-8306-8\\_6](https://doi.org/10.1007/978-1-4020-8306-8_6).
- Golubic, S., & Fischer, A. G. (1975). Ecology of calcareous nodules forming in Little Conestoga Creek near Lancaster, Pennsylvania. *SIL Proceedings, 1922–2010*, 19(3), 2315–2323. doi:10.1080/03680770.1974.11896313.
- Gradziński, M. (2010). Factors controlling growth of modern tufa: Results of a field experiment. *Geological Society, London, Special Publications*, 336(1), 143–191. <https://doi.org/10.1144/SP336.8>.
- Grotzinger, J. P., & Knoll, A. H. (1999). Stromatolites in Precambrian carbonates: Evolutionary mileposts or environmental dipsticks? *Annual Review of Earth and Planetary Sciences*, 27(1), 313–358. <https://doi.org/10.1146/annurev.earth.27.1.313>.
- Hunger, G. (2012). Reconstruction Paléoenvironnementale du Pleistocène sup.-Holocène au Nord de la Patagonie basée sur les lacs endoréiques Car-Laufquen, étude des lignes de côtes et stromatolites associés. Unpublished MSc Thesis, University of Geneva, Switzerland, 129 pp.
- Jahnert, R. J., & Collins, L. B. (2011). Significance of subtidal microbial deposits in Shark Bay, Australia. *Marine Geology*, 286(1), 106–111. <https://doi.org/10.1016/j.margeo.2011.05.006>.
- Jahnert, R. J., & Collins, L. B. (2012). Characteristics, distribution and morphogenesis of subtidal microbial systems in Shark Bay, Australia. *Marine Geology*, 303–306, 115–136. <https://doi.org/10.1016/j.margeo.2012.02.009>.
- Kalkowsky, E. (1908). Oolith und Stromatolith im norddeutschen Buntsandstein. *Zeitschrift der Deutschen Geologischen Gesellschaft*, 60, 68–125.
- Kaźmierczak, J., Kempe, S., Kremer, B., López-García, P., Moreira, D., & Tavera, R. (2011). Hydrochemistry and microbialites of the alkaline crater lake Alchichica, Mexico. *Facies*, 57(4), 543–570. <https://doi.org/10.1007/s10347-010-0255-8>.

- Kempe, S., Kaźmierczak, J., Landmann, G., Konuk, T., Reimer, A., & Lipp, A. (1991). Largest known microbialites discovered in Lake Van, Turkey. *Nature*, 349(6310), 605–608. <https://doi.org/10.1038/349605a0>.
- Kraus, E. A., Beeler, S. R., Mors, R. A., Floyd, J. G., GeoBiology 2016, Stamps, B. W., ... Corsetti, F. A. (2018). Microscale biosignatures and abiotic mineral authigenesis in little hot creek, California. *Frontiers in Microbiology*, 9, 997. <https://doi.org/10.3389/fmicb.2018.00997>.
- Krumbein, W. E. (1983) Stromatolites—The challenge of a term in space and time. *Precambrian Research*, 20(2), 493–531. [https://doi.org/10.1016/0301-9268\(83\)90087-6](https://doi.org/10.1016/0301-9268(83)90087-6).
- Merz-Preiß, M., & Riding, R. (1999). Cyanobacterial tufa calcification in two freshwater streams: Ambient environment, chemical thresholds and biological processes. *Sedimentary Geology*, 126, 103–124. [https://doi.org/10.1016/S0037-0738\(99\)00035-4](https://doi.org/10.1016/S0037-0738(99)00035-4).
- Noffke, N., Knoll, A. H., & Grotzinger, J. P. (2002). Sedimentary controls on the formation and preservation of microbial mats in siliclastic deposits: A case study from the Upper Neoproterozoic Nama Group, Namibia. *Palaios*, 17(6), 533–544. [https://doi.org/10.1669/0883-1351\(2002\)017<0533:SCOTFA>2.0.CO;2](https://doi.org/10.1669/0883-1351(2002)017<0533:SCOTFA>2.0.CO;2).
- Pacton, M., Hunger, G., Martinuzzi, V., Cusminsky, G., Burdin, B., Barmettler, K., ... Ariztegui, D. (2015). Organomineralization processes in freshwater stromatolites: A living example from eastern Patagonia. *The Depositional Record*, 1(2), 130–146. <https://doi.org/10.1002/dep2.7>.
- Pascuale Pérez, M. P., Carol, E., Alvarez, M. P., Eymard, I., Bilmes, A., & Ariztegui, D. (2019). Surface and groundwater hydrochemistry of the surroundings of The Lagunas Carri Laufquen. Actas de la V Reunion Argentina de Geoquímica de Superficie. La Plata 12 al 13 de Junio de 2019.
- Pedley, H. M. (1990). Classification and environmental models of cool freshwater tufas. *Sedimentary Geology*, 68(1–2), 143–154. [https://doi.org/10.1016/0037-0738\(90\)90124-C](https://doi.org/10.1016/0037-0738(90)90124-C).
- Pentecost, A. (2005). *Travertine*. Dordrecht, The Netherlands: Springer.
- Pentecost, A., & Viles, H. (1994). A review and reassessment of travertine classification. *Géographie Physique et Quaternaire*, 48(3), 305–314. <https://doi.org/10.7202/033011ar>.
- Petryshyn, V. A., Corsetti, F. A., Berelson, W. M., Beaumont, W., & Lund, S. P. (2012). Stromatolite lamination frequency, Walker Lake, Nevada: Implications for stromatolites as biosignatures. *Geology*, 40(6), 499–502.
- Rabassa, J., & Clapperton, C. M. (1990). Quaternary glaciations of the southern Andes. *Quaternary Science Reviews*, 9, 153–174.
- Reid, R. P., Macintyre, I. G., Browne, K. M., Steneck, R. S., & Miller, T. (1995). Modern marine stromatolites in the Exuma Cays, Bahamas: Uncommonly common. *Facies*, 33(1), 1–17. <https://doi.org/10.1007/BF02537442>.
- Riding, R. (2011a). Microbialites, stromatolites, and thrombolites. In J. Reitner & V. Thiel (Eds.), *Encyclopedia of geobiology* (pp. 635–654). Dordrecht, The Netherlands: Springer.
- Riding, R. (2011b). The Nature of stromatolites: 3,500 million years of history and a century of research. In Reitner, J., Quéric, N.-V., & Arp, G. (Eds.), *Advances in stromatolite geobiology* (vol. 131, pp. 29–74). Berlin, Heidelberg: Springer. [https://doi.org/10.1007/978-3-642-10415-2\\_3](https://doi.org/10.1007/978-3-642-10415-2_3).
- Roche, A., Vennin, E., Bouton, A., Olivier, N., Wattinne, A., Bundeleva, I., ... Visscher, P. T. (2018). Oligo-Miocene lacustrine microbial and metazoan buildups from the Limagne Basin (French Massif Central). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 504, 34–59. <https://doi.org/10.1016/j.palaeo.2018.05.001>.
- Ryves, D. B., Battarbee, R. W., Juggins, S., Fritz, S. C., & Anderson, N. J. (2006). Physical and chemical predictors of diatom dissolution in freshwater and saline lake sediments in North America and West Greenland. *Limnology and Oceanography*, 51(3), 1355–1368. <https://doi.org/10.4319/lo.2006.51.3.1355>.
- Schwalb, A., Burns, S. J., Cusminsky, G., Kelts, K., & Markgraf, V. (2002). Assemblage diversity and isotopic signals of modern ostracodes and host waters from Patagonia, Argentina. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 187(3), 323–339.
- Semikhatov, M. A., Gebelein, C. D., Cloud, P., Awramik, S. M., & Benmore, W. C. (1979). Stromatolite morphogenesis—Progress and problems. *Canadian Journal of Earth Sciences*, 16(5), 992–1015. <https://doi.org/10.1139/e79-088>.
- Solari, M. A., Hervé, F., Le Roux, J. P., Airo, A., & Sial, A. N. (2010). Paleoclimatic significance of lacustrine microbialites: A stable isotope case study of two lakes at Torres del Paine, southern Chile. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 297(1), 70–82. <https://doi.org/10.1016/j.palaeo.2010.07.016>.
- Suosaari, E. P., Reid, R. P., Playford, P. E., Foster, J. S., Stolz, J. F., Casaburi, G., ... Eberli, G. P. (2016). New multi-scale perspectives on the stromatolites of Shark Bay, Western Australia. *Scientific Reports*, 6, srep20557. <https://doi.org/10.1038/srep20557>.
- Tatur, A., del Valle, R., Bianchi, M.-M., Outes, V., Villarosa, G., Niegodysz, J., ... Debaene, G. (2002). Late Pleistocene palaeolakes in the Andean and extra-Andean Patagonia at mid-latitudes of South America. *Quaternary International*, 89(1), 135–150. [https://doi.org/10.1016/S1040-6182\(01\)00085-4](https://doi.org/10.1016/S1040-6182(01)00085-4).
- Vasconcelos, C., Warthmann, R., McKenzie, J. A., Visscher, P. T., Bittermann, A. G., & van Lith, Y. (2006). Lithifying microbial mats in Lagoa Vermelha, Brazil: Modern Precambrian relics? *Sedimentary Geology*, 185(3–4), 175–183. <https://doi.org/10.1016/j.sedgeo.2005.12.022>.
- Vennin, E., Bouton, A., Bourillot, R., Pace, A., Roche, A., Brayard, A., ... Visscher, P. T. (2018). The lacustrine microbial carbonate factory of the successive Lake Bonneville and Great Salt Lake, Utah. *Sedimentology*, 66(1), 165–204. <https://doi.org/10.1111/sed.12499>.
- Whitley, R. C., & Cusminsky, G. C. (1999). Lacustrine Ostracoda and late Quaternary palaeoenvironments from the Lake Cari-Laufen region, Rio Negro province, Argentina. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 151(1–3), 229–239. [https://doi.org/10.1016/S0031-0182\(99\)00022-X](https://doi.org/10.1016/S0031-0182(99)00022-X).

**How to cite this article:** Eymard I, Bilmes A, Alvarez MdP, et al. Growth morphologies and plausible stressors ruling the formation of Late Pleistocene lacustrine carbonate buildups in the Maquinchao Basin (Argentina). *Depositional Rec.* 2019;5:498–514. <https://doi.org/10.1002/dep2.81>